A PRELIMINARY ANALYSIS OF THE DEGREE AND NATURE OF BACTERIAL REMOVAL IN FILTRATION PLANTS[1]

By Abel Wolman

The determination of a law of bacterial removal by rapid sand water filtration plants is of great practical importance and utility. Such determinations of plant efficiencies are valuable as indicators not only of present but also of future performance. The objection is, however, often justly raised against the attempt to predict quantitatively the possibilities of bacterial removal, that existing numerical measures of performances are misleading and in some cases even harmful. The calculation of percentage removal from raw water to effluent is an illustration of the type of measure which has arithmetical accuracy, but little logical basis. It is quite evident, however, that it would be desirable to measure quantitatively the performance of a plant in such a way as to obtain a comparative conception of how well or how badly it is being operated.

Since at present no agreement exists among operators, designers, or public health officials as to a standard of "good performance," because, in the past, agreement has been prevented by the interminable search for a "standard effluent," itself the subject of disagreement, it becomes necessary to attack the problem of rating or standardizing plant accomplishment from another angle. In this discussion, an initial search is made for certain basic characteristics of rapid sand filtration. The term, rapid sand filtration, is here used more broadly than usually, to describe the entire process from preliminary coagulation through sedimentation or settling, filtration, and disinfection.

The measure of variable phenomena by comparison with ideal or "normal" conditions is a procedure common to scientific analysis. The application of this method offers here a fruitful means of testing our ideas of filtration efficiency. The first problem obviously consists in the attempt to determine a possible correlation between the

[1] Read before the St. Louis Convention, May 15, 1918.

number of bacteria in the final effluent of a filtration plant and the number in the raw water. A numerical statement of the problem should be clearer. If a plant uses a raw water containing 500 bacteria per cubic centimeter and produces an effluent containing 10 per cubic centimeter, will the same plant produce an effluent of 20 per cubic centimeter when the raw water content is 1000 per cubic centimeter? Can one predict, in other words, with any degree of precision, what effluent counts should be normally attainable with varying raw water counts?

The use of a "percentage efficiency" is of but little value in the solution of this problem, since that measure is predicated upon the very assumption that the effluent counts vary directly, rather than more complexly, with raw water counts. The fallacy in this view need hardly be demonstrated at this late period in the development of filtration practice.

The norm or ideal performance from which it is possible to obtain hypotheses as to standard empirical accomplishment is not difficult to deduce. The "normal empirical performance" may be defined as the accomplishment of a filtration plant which is known to be operating successfully. Successful operation can be said to exist wherever there is an unquestioned superior bacteriological and physical quality of effluent, consistent performance, excellent control, and scientific observation of operating details. Plants whose performance may be used as the basis for comparison and for the derivation of the law of bacterial removal, are not at all rare. In this analysis, the operating statistics of the filtration plant at Avalon, Maryland, owned by the Baltimore County Water & Electric Company and operated by S. T. Powell, were used.

This plant obtains its raw water from the Patapsco River, a highly polluted stream, ranging in turbidity during the year from 0 to 5000 parts per million and in bacterial content (20°C. gelatine-48 hours), from several hundred to 150,000 per cubic centimeter. The watershed of the stream is composed largely of cultivated areas, with no large sewage polluting influences. This water is treated with aluminum sulphate, at an average rate of 0.8 grain per gallon, and is then allowed to settle for four hours. After leaving the sedimentation basin it is treated with calcium hypochlorite with an average dose of 0.34 part per million, and then passes through the rapid sand filters which have a capacity of 2,500,000 gallons per day.

The plant is controlled scientifically by a trained operator with the aid of modern equipment and laboratory observation. During several years of operation the bacterial content of the effluent has not exceeded, at any time, 20 bacteria per cubic centimeter. Presumptive tests for B. coli in lactose broth have indicated positive tests in 1 cc. less than 2 per cent of the time during any year. The

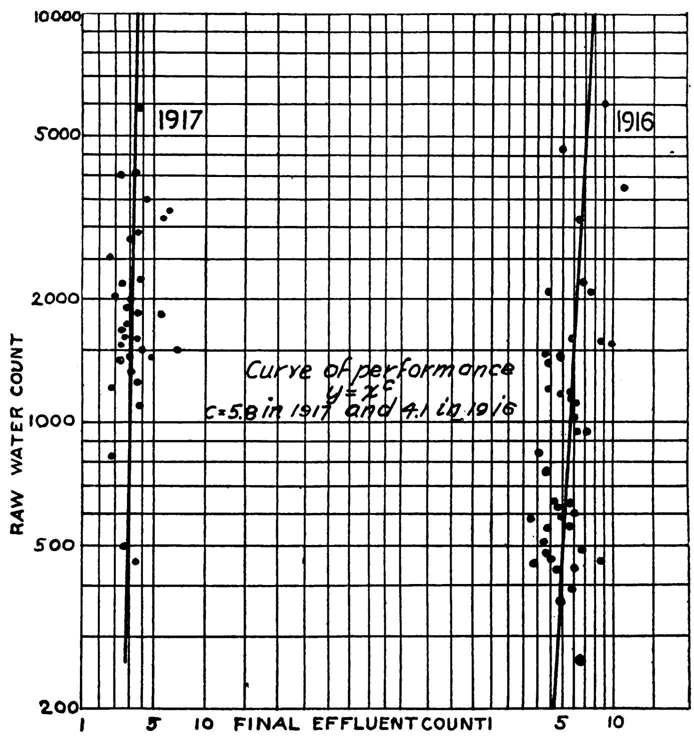

FIG. 1. BACTERIAL REMOVAL BY THE AVALON RAPID SAND FILTRATION PLANT DURING 1916 AND 1917; 20°C. BACTERIAL COUNTS USED

number and kinds of bacteria are determined in raw water and final effluent every day and general experimental data are constantly collected.

It is clear, therefore, that the plant in Baltimore County approaches so closely, from the standpoint of operating results, the ideal plant as to justify the use of its performance as the basis of a law of filtration.

In order to determine with some degree of accuracy the form of a characteristic empirical performance curve, the results of raw water and final effluent counts of the Avalon plant were plotted on figure 1.

In order to avoid plotting a mass of points which would tend to confuse the reader, seven-day averages of both stations, rather than daily results extending over a period of nineteen months in 1915, 1916, and 1917, were used. In plotting these values, approximately 520 daily analyses were summarized. These were obtained in consecutive months and under every phase of operating conditions. No counts were discarded as being unfair or incorrect. Figure 1 represents, therefore, the normal daily performance of the plant for more than a year and a half.

A study of the samples plotted on figure 1 reveals at once a consistency of arrangement. It is clear, too, that the performance of this normal plant is represented by the curves shown on figure 1. Inasmuch as these curves are practically straight lines, within the limits shown, the derivation of their equation is simple. The equation of a straight line, when the results have been plotted on a logarithmic basis, is given by: $c = \log y \div \log x$, where c is a constant for this particular plant, and y and x are respectively the raw water and final effluent counts.

It would appear, therefore, that the "normal empirical performance" is represented by a curve having the equation: $y = x^c$. A tentative hypothesis, with regard to bacterial removal by filtration action, may be promulgated, therefore, as follows: The final effluent count, under normal operating conditions, is an exponential function of the raw water count. This hypothesis provides a means of determining whether or not a plant under scrutiny is, at least, "performing normally," where normal performance would be interpreted as conformity to the logarithmic curve of filtration. Figure 2 illustrates, for instance, the failure of plant A to perform its function efficiently. By comparing the points on figure 2 showing the operating statistics of plant A with the points and the form of resultant curves in figure 1, it becomes clear that the plant A is erratic in performance in so far as the graphic representation of its operation departs from what we have reason to believe is a characteristic form of ideal curve of bacterial removal.

The "normal performance" curve demonstrates the fallacy of assuming that the *difficulty* of removal of bacteria is relatively the same regardless of the number of bacteria in the raw water. Although this assumption is rarely publicly proclaimed, it is usually summoned, however, to the aid of those plants which, for one reason or another, are so unsuccessful as to require a specious hypothesis,

fairly reasonable to the layman, to support their claims to maximum efficiency of 99 per cent plus. The practical results of a scientifically controlled plant certainly seem to lead to the conclusion that increases in raw water bacterial content decrease the corresponding bacterial content *interval* in the final effluent.

It should be added, too, that the equation of normal performance, $y = x^c$, offers a new quantitative measure of the efficiency of any plant, obtained by evaluating in any case the constant, c. Such a

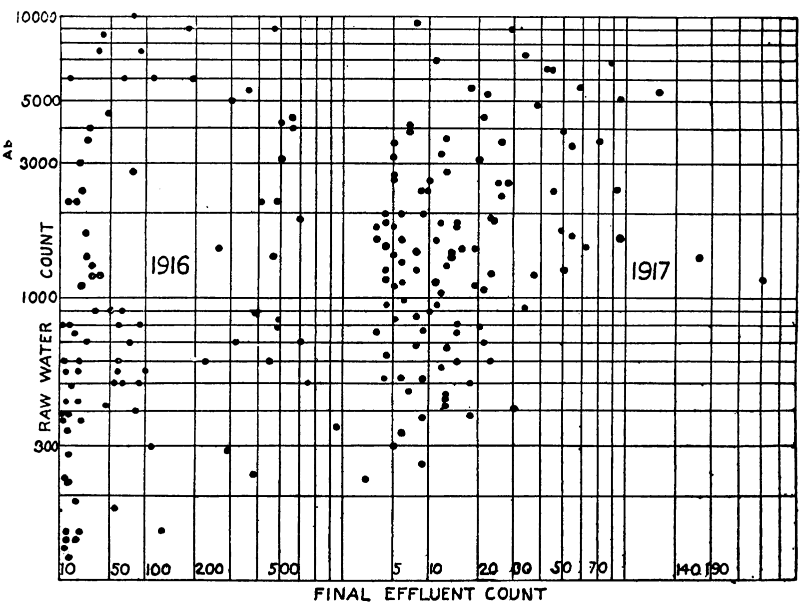

FIG. 2. INCONSISTENCY OF PERFORMANCE OF PLANT A AS INDICATED BY 20°C. COUNTS

measure, among other qualities, has the advantage of a rational basis and of a practical significance. Its use has been discussed elsewhere[2] by the author.

What absolute value this constant, c, or the so-called "coefficient of efficiency," should attain is dependent upon individual opinion of "good performance." It is of interest to note, however, that, in a survey of 19 rapid sand filtration plants, varying in size from 2.2 to 80.0 million gallons filtered per day, the coefficient of efficiency of these plants has attained an annual average of over 2.5. The raw

[2] *Jour. Amer. Pub. Health Assoc.*, November, 1916.

waters which these plants had to treat contained turbidities ranging from an annual average of 1 to 561 parts per million, and average bacterial contents from 350 to 16,500 per cubic centimeter. The 19 plants chosen, therefore, for the evaluation of c, are representative, in their initial conditions, of rapid sand filtration.

The probable existence of the law of filtration, $y = x^c$, combined with known values of c, practically attainable, gives the investigator

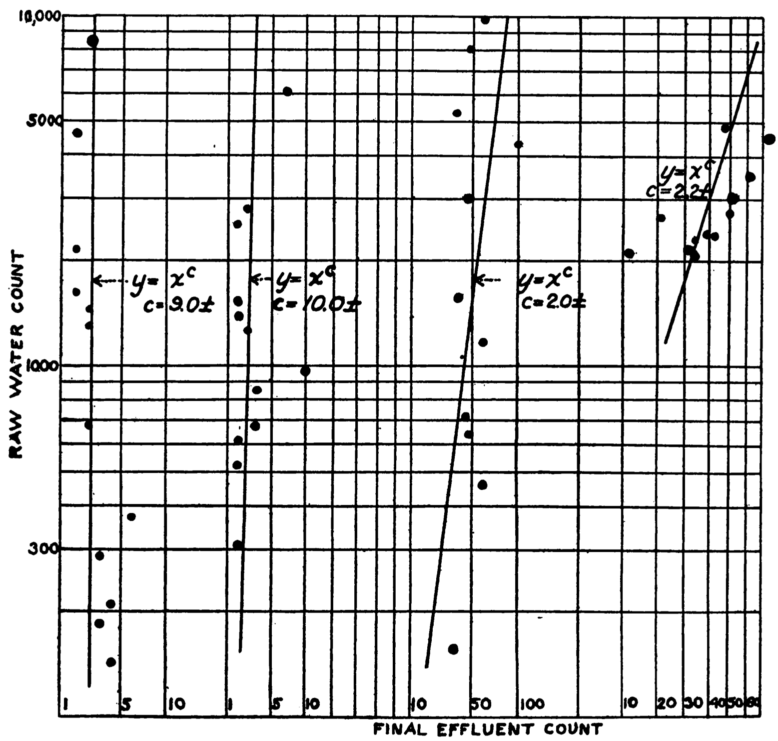

FIG. 3. PERFORMANCE CURVES OF FOUR LARGE RAPID SAND FILTRATIGN PLANTS

of filtration plant accomplishment the fundamental criteria with which to measure both the character and the amount of removal in any particular plant. The objection may be raised to the above method of critical standardization of plants, that all do not function in a similar manner, on account of differences in raw water, resulting from peculiarities of suspended matter, variations in resistance of

bacteria, and other similar factors. This objection does not seem to the author to be entirely valid, since peculiar characteristics of raw water are usually provided for by variations in design, such as increased periods of sedimentation and greater doses of disinfectant. It is reasonable to suppose, therefore, that given plants, initially properly designed for local conditions, should function according to some common law, since death rates under disinfection, devitalization and sedimentation and filtration of bacteria differ in the degree, but not in the kind, of changes effected.

The preliminary theory of bacterial removal by filtration is supported by the curves shown in figure 3, where are plotted the average monthly results from several large rapid sand plants in the United States. The monthly, instead of the weekly, results are used since the latter were not obtainable. The form of curve would be the same in both instances, while the value of the constant may change. It is quite obvious that each plant follows in its performance the characteristic $y = x^c$ curve.

Since the death-rate of bacteria under the action of disinfectants, and under well defined conditions, has been shown,[3] to follow in general the law: $c = \frac{1}{t_2 = t_1} \log \frac{y}{x}$, it will be necessary to look for the causative factors of the $y = x^c$ law in other phases of the system of rapid sand filtration. It is the author's purpose to study further the bacterial removal in the individual and distinct processes of coagulation, sedimentation, and filtration proper, with a view to throwing further light on the problem of causation.[4]

[3] H. Chick, *Jour. of Hygiene*, Vol. 8, 1908; Vol. 10, 1910.

[4] Strictly speaking, the equation of a straight line curve plotted on logarithmic axes is: $y = bx^c$, where b is the intercept on the y axis. In that case, c becomes $\frac{\log y - \log b}{\log x}$ rather than $\frac{\log y.}{\log x}$ Log b is infinitely small in our particular problem, since b, the intercept on the y axis, would be equivalent to those raw water counts which produce resultant final effluent counts of one. Since zero counts are rarely obtained in filtration plants, even with extremely low raw water counts, it is conceivable that the performance curve in the "normal operation" described above would intercept the y axis at some point approaching unity. Log b, therefore, would approach zero and could be neglected in the evaluation of c. It is evident, therefore, that $c = \frac{\log y}{\log x}$ measures in each case, with sufficient accuracy, the slope or inclination of the performance curve, the significant index to the efficiency of bacterial removal.